Enabling cutting tool services based on in-process machining condition monitoring

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Abstract: The cutting tool industrial product-service system (ct-iPSS) integrates intangible cutting services with physical cutting tools to satisfy consumers’ cutting/machining requirements. It realises a win-win situation for cutting tool service consumers, cutting tool manufacturers and the third-party cutting tool service providers. However, the study on ct-iPSS is insufficient when some significant topics are still pending. In this paper, the in-process cutting tool condition monitoring service is integrated in the improved ct-iPSS model. A more precise cutting tool demand prediction service is enabled on the basis of in-process cutting tool reaming useful life prediction service. The used cutting tool collection routes are optimised together with the new cutting tool delivery routes. The total delivery/collection cost is minimised systematically to enable a more feasible ct-iPSS. A scenario is presented to verify these services. The ct-iPSS’s feasibility and practicality are enhanced by the improved ct-iPSS model.

Keywords: industrial product-service system; PSS; cutting tool service; machining condition monitoring.


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1 Introduction

Integrating products and services is a growing trend among companies in today’s globally competitive business environment. The concept of product-service system (PSS) was proposed to fulfil customers’ needs in an economical and sustainable manner (Mont, 2002). Moreover, the industrial PSS (iPSS or IPS2) (Reim et al., 2015) was an integration of industrial products and the production-related services (Meier et al., 2011). By providing these services, iPSSs accelerated resource sharing among industries. The concept of everything as a service (EaaS) also triggered industrial product-service innovation (Gao et al., 2015; Tao et al., 2015). Through creating various new business models, iPSS discovered some new profit sources for industries. However, insights about how to implement a successful iPSS are still very limited (Baines et al., 2007; Gaiardelli et al., 2014). Because the product-service models have not been discussed extensively (Meier et al., 2010), a big research gap exists between the ideal and the reality. A better understanding of iPSS implementation in a specific field is needed urgently.

Especially, the cutting tool iPSS (ct-iPSS) integrates intangible cutting services with physical cutting tools to satisfy consumers’ cutting requirements (Sun et al., 2016b). By prolonging the business chains, traditional cutting tool manufacturers turned to ct-iPSS providers. Moreover, the third-party ct-iPSS providers were also available. Both of them had professional skills about cutting tools and provided excellent professional cutting services. In the ct-iPSS model, the cutting tools are owned by the service providers. Cutting service consumers pay for the intangible cutting tool services only. Their requirements can be fulfilled without focusing on the physical cutting tools. It is expected that ct-iPSS helps cutting tool service consumers, cutting tool manufacturers and the third-party cutting tool service providers to realise a win-win situation (Lindahl et al., 2014).

However, the study on how to implement such a ct-iPSS is very limited. Although a just-in-time cutting tool delivery service was developed based on a cutting tool demand prediction model (Sun et al., 2016b), the ct-iPSS could also be improved further. The integration of tool condition monitoring (TCM) has shown great potential in improving ct-iPSS (Zhang and Sun, 2017). However, how to create TCM-based value-added services is still a question. Something should also be done to improve the availability of cutting tool services. All these issues are going to be discussed in this paper to improve ct-iPSS.

The rest of this paper is organised as follows. Section 2 presents a brief review of literature related to PSS/iPSS and cutting tool services. Section 3 proposes the overall model of the improved ct-iPSS. In Section 4, basic cutting tool monitoring services and value-added service are regarded as key enabling technologies and discussed in detail respectively. A scenario is demonstrated in Section 5, which is followed by concluding remarks in Section 6.
2 Literature reviews

2.1 PSS/iPSS

An iPSS was an integration of industrial products and related services that delivers values in industrial applications (Reim et al., 2015). The iPSS provided services over the whole life cycle to enhance customer value (Meier et al., 2011). It also accelerated the resource and capability sharing among industries. Almost everything related to product and production could be treated as an iPSS, including design services, manufacturing services, simulation services, computing services, etc. (Tao et al., 2015). Therefore, many iPSSs have been studied and developed. For example, the iPSS for CNC machine tool (Zine et al., 2014) integrated machine tools with technical services regarding operations, repairs and maintenances (Zhu et al., 2011). Regarding the warehouse product service system (wPSS) the intangible services were attached to the tangible storage cells (Cao and Jiang, 2013). Machine availability monitoring and process planning were also encapsulated as an iPSS (Wang, 2013).

Recently, the in-process condition monitoring has showed great potential for iPSS (Morgan and O’Donnell, 2015). For example, DMG MORI Messenger provided machine tool monitoring services on various mobile devices including tablets and smart phones (DMG MORI Messenger, 2016). The SKF @ptitude Connect enabled online bearing monitoring and maintenance decision-making (SKF @ptitude Analyst, 2016). As a third party service, the VIMANA Core system provided real-time shop floor monitoring service to help customers manage the productivity of their machine tools (VIMANA, 2017). The ‘smart tools’ iPSS project, implemented a modular sensor platform with a connected diagnostic unit for injection moulding tools (Schuh et al., 2014).

2.2 Cutting tool services

Nowadays, cutting tool services are becoming more and more popular (Sakao and Shimomura, 2011). By using ct-iPSS, consumers can achieve much more professional cutting tool service with much lower cost. The ct-iPSS providers can also benefit greatly from the cutting tool services. Therefore, many traditional cutting tool manufacturers have prolonged their value-added chains by providing cutting tool services. For example, the COMET ToolScope system (COMET ToolScope, 2016) provided some process and cutting tool monitoring services, including cutting tool breakage, collision, uneven running, vibrations, and so on. The ct-iPSS can also be operated by the third party cutting service providers (Chen et al., 2011). For example, the Tool Consulting & Management Group has been providing cutting tool management services for Shanghai General Motors (SGM) for a few years (TCMG, 2016). In this way, a win-win situation appeared among the cutting tool service consumers, cutting tool manufacturers, and third-party cutting service providers. Based on TCM, an iPSS model has been proposed to enable successful cutting tool services. Two service procedures were respectively designed for product-oriented mode and use-oriented mode (Zhang and Sun, 2017).

Although ct-iPSS has brought such a valuable business model, its implementation is still studied insufficiently. Some significant topics should be investigated to make ct-iPSS more professional and feasible. For example, the cutting tool demand could be predicted more precisely by integrating in-process machining condition services. Considering the
cutting tools’ ownership and recycle requirement, the collection route of used cutting tools should also be optimised in addition to the delivery route optimisation only (Sun et al., 2016b). The intangible services of a ct-iPSS could be available ubiquitously by using mobile computing technology.

In summary, the concept of iPSS accelerated the resource and capability sharing among industries. The ct-iPSS brought a win-win business model for cutting tool service consumers, cutting tool manufacturers and the third-party cutting tool service providers (Sun et al., 2016b). However, the study regarding to its implementation is insufficient. Some significant topics, such as the machining condition monitoring service, the cutting tool delivery/collection optimisation and ubiquitous service availability, could be developed or integrated to enhance ct-iPSS’s feasibility and practicality.

3 The improved ct-iPSS model

3.1 Framework of the improved ct-iPSS

The improved ct-iPSS provides cutting tool service based on in-process TCM. As an integration of industrial products and services, it involves both hardware and software. Based on acquired in-process signals and data, it monitors tool condition and evaluates remaining useful life (RUL) by using professional knowledge and artificial intelligence. Moreover, it also presents some value-added services, such as cutting tool demand prediction, tool allocation configuration, tool delivery optimisation, and so on. Improved ct-iPSS makes its intangible services available ubiquitously via the mobile computing technology. The framework of the improved ct-iPSS is shown in Figure 1.

Figure 1 The overall framework of the improved ct-iPSS (see online version for colours)

To enable the cutting tool service, the implementation of the improved ct-iPSS includes the following five steps.
Enabling cutting tool services

1. Original signals and data acquisition. Prior to providing any services, the original signals and data must be acquired. Here, some sensors are used to collect in-process signals, including force, vibration, acoustic emission, temperature, etc.

2. Sensitive feature extraction. Due to the limitation of bandwidth, it is more reasonable to process the original signals and raw data locally, instead of transferring them via the network. Besides statistical techniques and time or frequency domain decomposition methods, some adaptive decomposition methods, including empirical mode decomposition (EMD) and local mean decomposition (LMD), are also used to decompose the original signals. Based on the prior knowledge and processed results, some sensitive features are extracted for further decision-making.

3. In-process TCM services. Based on extracted sensitive features, some TCM services are enabled. Typical examples include cutting tool wear condition monitoring, tool reliability monitoring, tool RUL prediction, and so on. Normally, machine learning skills, including back propagation neural network (BPNN), support vector machine (SVM), deep learning, etc., can be adopted to build decision-making models. Moreover, many models are trained to evaluate tool wear conditions or to predict cutting tool RUL for various machining conditions. Based on service requirements, a suitable model may be matched. Then, the corresponding features, signals and sensors can be configured in sequence (Zhang and Sun, 2017).

4. Value-added services. Some value-added services are enabled based on in-process TCM services. Normally, they are cutting tool warehouse allocation service, demand prediction service, delivery/collection route optimisation service, etc. Normally, these services are provided offline.

5. Ubiquitous service availability. The intangible services are available ubiquitously based on the mobile computing technology. In addition to broadcast and access, a service can also be pushed to its subscribers. To balance the requirement of private protection and service sharing, the service accession control policy may apply.

3.2 Service encapsulation steps

To implement the improved ct-iPSS, both online services and offline services are encapsulated. The encapsulation steps are shown in Figure 2 and discussed in detail as follows.

1. Prior to provide services, the basic environment must be deployed. Firstly, typical sensors are mounted around the machine tool to acquire force, vibration, acoustic emission and temperature signals. Some signal processing, feature extraction and decision-making algorithms are developed. Database and knowledge are also ready for use.

2. A cutting tool service requirement delivers the voice of service consumers. To enable such a service, the cutting tool type, machining condition and cutting service time are specified clearly in advance.

3. Considering the service requirement, hardware and software should be configured on the basis of service deployment. Some sensors are selected and the corresponding parameters are set. As to software, algorithms for signal processing, feature
extraction and decision-making are configured accordingly. The service accession control policy and the service templates are also configured.

4 A cutting tool service requirement is fulfilled by the in-process TCM services and the offline cutting tool delivery/collection service. The in-process TCM services are available ubiquitously. Both regular services and emergent services are included as follows:

- Time-dependent services are available at a fixed frequency. For example, the cutter wear condition monitoring service is provided every five minutes.
- Event-dependent services are available when some pre-defined events occur. For example, service consumers are informed when the cutter wear condition is 0.1 mm, 0.2 mm or 0.3 mm.
- Alarm services are triggered by some emergent events, such as rapid cutter wear, tool broken, tool collision, etc.

In addition, some information components, including the destination, the route, new cutters to be delivered and used cutters to be collected, are included. Based on the positioning service, the cutting tool delivery/collection operations are encapsulated as location-based offline services. The map services are integrated to enable guide services. At a destination, cutters to be delivered and collected are checked by using automatic identification equipment. If the internet-of-thing (IoT) technology is integrated, the delivery/collection operation can be implemented in a more automatic and intelligent mode.

Figure 2 Service encapsulation steps (see online version for colours)
4 Enabling technologies

4.1 Basic services

4.1.1 In-process TCM

In order to enable the in-process TCM service, the original signals and raw data are processed. Besides Fourier transform and wavelet transform, EMD and LMD methods are also used to achieve high precision both in time domain and frequency domain at the same time. Take EMD for example, the original signal $x(t)$ is decomposed into several intrinsic mode function (IMF) components and a residual as

$$x(t) = \sum_{i=1}^{n} c_i + r_n$$

(1)

Here, $c_i$ is the $i^{th}$ IMF component and $r_n$ is the residual after $n$ times of decomposition. The Hilbert transform is used to calculate the Hilbert time-frequency spectrum as

$$H(\omega, t) = \text{Re} \sum_{i=1}^{d} a_i(t) e^{j\omega(t)dt}.$$  

(2)

Here, $a_i(t)$ and $\omega_i(t)$ are functions of time. The function Re means that only the real parts are included.

Sensitive features are extracted by looking through the signal characteristics when the machining condition is developing. Normally, the average amplitude of an IMF and the maximum amplitude in the Hilbert marginal spectrum are extracted.

The characteristic matrix $X = [X_1, X_2, \ldots, X_M]$ which is made up of sensitive features, are mapped to a higher dimension space $F$ by a nonlinear mapping function $\phi$ as $\phi(X) = [\phi(X_1), \phi(X_2), \ldots, \phi(X_M)]$. The kernel principal component analysis (KPCA) method is used to decouple correlation relationship and reduce redundant information in the characteristic matrix. The top $r$ vectors are selected to make a subspace matrix according to their accumulative contributions. The matrices under normal state and running state are constructed respectively. The principal angle between them is calculated by using the singular value decomposition (SVD) method. The cosine value of the minimum principal angle is calculated as the operational reliability (OR) value of a cutting tool as follow.

$$R = \cos \left( \min (\theta_i) \right), i = 1, 2, \ldots, d$$  

(3)

Here, $\theta_i$ is the $i^{th}$ principal angle of the $i^{th}$ eigenvalue.

As Figure 3 shows, the OR value, feed rate, spindle speed and cutting depth are input parameters of the BPNN model, when the cutting tool RUL value is the output. Considering the scope and length of this paper, more detailed discussion about in-process cutting tool RUL evaluation is not included. Please refer literature Sun et al. (2016a) for further information. However, the nonlinear cutting tool wear process and varying machining conditions should be considered to improve this BPNN model or to build better machine learning models.
4.2 Value-added services

Based on in-process cutting TCM, some value-added services are developed. Typical examples include cutting tool requirement prediction, warehouse allocation configuration, delivery/collection route optimisation, and so on. To enable the cutting tool service, the cutting tool requirement prediction service and the delivery/collection route optimisation service are going to be discussed in detail.

4.2.1 Cutting tool demand prediction service

Prior to computing the reliable cutting time, the cutting tool demand should be predicted in advance. Normally, it is based on statistical result of history data or the emendatory Taylor formula. As to cutting tool type $i$, the cutting time requirement in process $j$ is calculated as follow.

$$
L_{i,j} = \frac{t_j n_i z_i}{T_i}
$$

where $t_j$ is machining time of process $j$, $n_i$ is the required volume of work pieces, $z_i$ is teeth-number of the cutting tool, $T_i$ is life expectation of cutting tool type $i$ which is calculated by the following emendatory Taylor formula.

$$
T = \frac{C_m C_r}{(v_c)^{1 \over h} f^{1 \over g} (a_p)^{1 \over h}}
$$

where $v_c$ is cutting-speed, $a_p$ is cutting depth, $f$ is feed rate. $C_m$ and $C_r$ are the correction coefficients related to tool manufacturers and machining conditions respectively, $m$, $g$ and $h$ are impacts of the tool life caused by $v_c$, $f$ and $a_p$ respectively. The total machining time requirement of cutting tool $i$ is calculated as:
Enabling cutting tool services

\[ L_i = \sum_{j=1}^{J} L_{i,j} \tag{6} \]

where \( J \) is the amount of procedures. The requirement of cutting tool type \( i \) is calculated by:

\[ r_i = \text{Ceil} \left( \frac{L_i}{T_i} - W_i \right) + s_i \tag{7} \]

where \( W_i \) is the volume of cutting tool type \( i \) in the warehouse, \( s_i \) is the safe inventory quantity of cutting tool type \( i \). The function \( \text{Ceil}() \) returns the smallest integer greater than or equal to a given decimal.

In fact, the cutting tool service requirement is always changing due to the dynamical property of machining order. The lives of cutting tools always vary greatly. More reasonable cutting tool demand prediction should consider the in-process TCM result. As to customised or long-life cutting tools, the demand is calculated based on the RUL evaluation result of each individual cutting tool. The demand of cutting tool type \( i \) for the next day is calculated by:

\[ \hat{n}_i = \text{Ceil} \left( \frac{L_i - l_i^0}{T_i} - W_i \right) + s_i \tag{8} \]

where \( l_i^0 \) the RUL evaluation of the cutting tool which belongs to type \( i \).

4.2.2 Cutting tool delivery/collection route optimisation service

To ensure the cutting time, the service provider tries to deliver required cutting tools timely. In addition, used cutting tools should also be collected. The delivery/collection routes are optimised to fulfil all customers’ requirements on time and minimise the total cost. It is a typical combinational optimisation problem when number of vans and delivery routes are variables.

The total amount of cutting tools to be delivered is,

\[ DR = \sum_{i=1}^{I} \sum_{k=1}^{K} d_{rik} \tag{9} \]

where \( I \) is the number of tool type, \( K \) is the number of service consumers, \( d_{rik} \) means the amount of tool type \( i \) to be delivered to service consumer \( k \). The total amount of cutting tools to be collected is,

\[ CR = \sum_{i=1}^{I} \sum_{k=1}^{K} c_{rik} \tag{10} \]

where \( c_{rik} \) is the amount of tool type \( i \) to be collected from service consumer \( k \).

The initial van requirement is calculated by:

\[ VR = \text{Ceil} \left( \frac{\max(DR, CR)}{S} \right) \tag{11} \]
where $S$ is the maximum capacity of each van.

As to van $i$, the delivery/collection cost is calculated by,

$$C_i = C_{bi} + R_i C_{ni}$$  \hspace{1cm} (12)$$

where $C_{bi}$ is the basic fee per time per van, $R_i$ is the total route length and $C_{ni}$ is the normal fee per unit distance. The optimisation goal is to minimise the total cost as:

$$C = \min \sum_{i=1}^{N} C_i$$  \hspace{1cm} (13)$$

Two constraints must apply. One is that the maximum delivery/collection time should be no more than the time expectation $LT$.

$$\max(T_1, T_2, ..., T_{VR}) \leq LT$$ \hspace{1cm} (14)$$

The other is that each van should not be overloaded during the delivery/collection process, which means the capacity limit $LC_i$ should not be exceeded as.

$$0 \leq l_{ik} - d_{ik} + c_{ik} \leq LC_i$$ \hspace{1cm} (15)$$

where $l_{ik}$ is the load of van $i$ at destination $k$, $d_{ik}$ and $c_{ik}$ are tools to be delivered to and to be collected from destination $k$ respectively.

**Figure 4** The problem-solving procedure
To solve this problem, an algorithm is designed based on particle swarm optimisation (PSO). The procedure is shown in Figure 4. Firstly, the starting position of $M$ particles is generated randomly. When every particle’s fitness is calculated, the best position and its fitness can be found. The iteration continues until the counter $NC$ is no less than the limitation $NC_{\text{max}}$. In each iteration, every particle studies to its previous position, its best position in history and the global best position according to possibility. The study procedure repeats until every particle updates its position. Every particle’s best position and the global best position are also updated accordingly.

A solution to the problem is the delivery/collection sequence set of all vans. For a van, the route is a set of the customers’ number in order. Routes of all vans’ are connected by the special char ‘0’. For example, three vans can serve 17 customers by the following solution.

$$4, 8, 7, 12, 6, 0, 2, 16, 9, 13, 1, 0, 15, 11, 17, 5, 14, 3, 10$$  \(16\)

The maximum delivery time constraint in equation (14) is satisfied by the following penalty function.

$$P_T = \left( \max(T_1, T_2, \ldots, T_{VR}) - LT \right)^2$$  \(17\)

The capacity limit constraint in equation (15) is satisfied by the following penalty function.

$$P_C = \sum_{i=1}^{m} \sum_{k=1}^{K} \left( d_k - d_{ik} + c_{ik} \right)^2$$  \(18\)

The optimisation goal expressed by equation (13) is converted into the following fitness function.

$$F = C + P_T + P_C$$  \(19\)

## 5 Scenario

To illustrate the improved ct-iPSS, a prototype is developed. As Figure 5 shows, a three-axis milling machine (Carver WMS1200H) is used. A Kistler 9367C force sensor, a Kistler 8766A50 accelerometer and a Kistler 8125B121 acoustic emission (AE) sensor are adopted. Signals are collected by the DEWSOFT-43 portable data acquisition. Both feature extraction and in-process TCM service are implemented locally. The result is saved in the SQL Server 2008 database via the internet. Tomcat 7.0 is used to make the service available ubiquitously. Every GET request is responded by a corresponding Servlet. Both APP client and JSP pages can access the services. The Android Studio 1.3.2 is used to develop and simulate the mobile computing environment. A smart phone, Huawei MT7-UL00, is also used to assess the services.

As Figure 6 shows, the intangible services of the improved ct-iPSS are available on a smart phone emulator. The service provider can provide in-process condition monitoring service for several cutting tools at the same time. Both acquired signals and extracted features can be accessed. RUL of every cutting tool can be evaluated. Then the demand of every cutting tool type can be predicted and illustrated by a column diagram.
Figure 5  The prototype setup (see online version for colours)

Figure 6  In-process TCM services (see online version for colours)
In order to provide reliable cutting tool service, the delivery/collection route is optimised based on above cutting tool requirement prediction result. As Figure 7 shows, three vans are used to provide cutting tool delivery/collection services for 28 customers. Every van’s route is highlighted by certain line type. The delivery/collection sequence of a van is shown by numbered locations. The route optimisation algorithm is implemented and tested in MATLAB 2012. The particle population size is 50. Every particle studies to its previous position, its best position and the global best position according to the possibilities 0.5, 0.6 and 0.1 respectively. After 200 iterations, every van’s route is optimised to minimise the total delivery/collection cost.

**Figure 7** Cutting tool delivery/collection route optimisation (see online version for colours)

**Figure 8** Cutting tool delivery/collection service (see online version for colours)
As Figure 8 shows, the delivery/collection operations can be encapsulated as offline location-based services. The guide services can be enabled by using the location parameters. The cutting tool check list can be used to make sure that right tools are going to be delivered to or collected from right place at right time. As a result, both online services and offline services of the improved ct-iPSS are implemented. They are used to enable the cutting time services.

In summary, some machining condition monitoring services are developed and integrated in the improved ct-iPSS model. Similar to machine tool services, they are professional services regarding to every cutting tool. The in-process cutting tool RUL prediction service is developed in addition to the cutting tool life calculation based on the emendatory Taylor formula only. Therefore, the cutting tool demand could be predicted more precisely. Rather than the cutting tool delivery routes, the collection routes of used cutting tools are also considered. They are optimised globally to minimise the total delivery/collection cost. A close-loop cutting tool service mode is built by considering cutting tool delivery and collection systematically. Moreover, the intangible services of the improved ct-iPSS are available ubiquitously on the basis of mobile computing technology.

Although this work improves ct-iPSS greatly, some limitations still exist. The in-process machining condition monitoring services are far from real time services. The inevitable time delay decreases the feasibility and practicability of the improved ct-iPSS. Only cutting tool demand prediction and delivery/collection service are developed as value-added services. More services, such as cutting tool allocation configuration service and performance evaluation service, should be implemented to improve ct-iPSS. In addition, minimising the total cost is the unique goal in cutting tool delivery/collection route optimisation. In fact, the time consumption and vans’ load can also been considered to build a multi-objective route optimisation model. The service accession control policy should be introduced to balance the requirement of private protection and service sharing.

6 Conclusions

Against the background of iPSS, an improved ct-iPSS model is put forward on the basis of machining condition monitoring. The in-process cutting TCM services are basic services, while tool demand prediction and tool delivery/collection route optimisation are value-added services. A scenario is presented to verify the feasibility. The following conclusions can be drawn.

- The in-process cutting TCM service is integrated in the improved ct-iPSS model. A more precise cutting tool demand service is enabled on the basis of in-process cutting tool RUL prediction service.
- The used cutting tool collection routes are optimised together with the new cutting tool delivery routes. The total delivery/collection cost is minimise systematically to enable a more feasible ct-iPSS.

Although this work improves ct-iPSS’s feasibility and practicality, some limitations call for further researches. Cutting tool allocation configuration service and performance evaluation service are needed to enhance ct-iPSS further. Besides the total cost, time consumption and van’s load should be considered in the multi-objective cutting tool
Enabling cutting tool services

delivery/collection route optimisation. Additional work to decrease the time delay of machining condition monitoring services should also be explored. The service accession control policy should be studied too.

References


